Mutual Coupling Reduction Between Microstrip Patch Antennas Using Slotted-Complementary Split-Ring Resonators

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***Abstract*—A novel structure based on complementary split-ring resonators (SRRs) is introduced to reduce the mutual coupling between two coplanar microstrip antennas that radiate in the same frequency band. The new unit cell consists of two complementary SRR inclusions connected by an additional slot. This modification improves the rejection response in terms of bandwidth and suppression. The filtering characteristics of the band-gap structure are investigated using dispersion analysis. Using the new structure, it was possible to achieve a 10-dB reduction in the mutual coupling between two patch antennas with a separation of only 1/4 free-space wavelength between them. Since the proposed structures are broadband, they can be used to minimize coupling and co-channel interference in multiband antennas.**

***Index Terms*—Complementary split-ring resonators (CSRRs), defected slots, low-profile antennas, microstrip patch antennas, mutual coupling.**

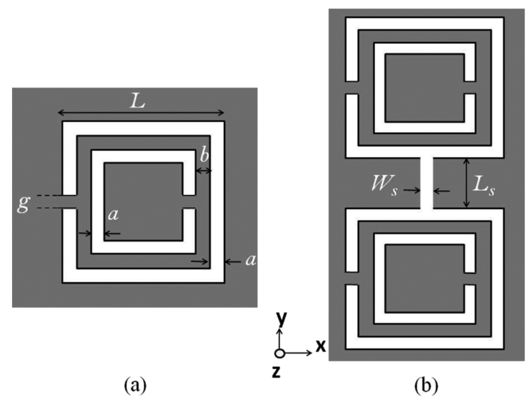

Fig. 1. (a) CSRR unit cell. (b) Proposed SCSRRs unit cell. Note that the gray shaded area represents metallization, and the figure is not drawn to scale. E-field is normal to the axis of both CSRR and SCSRR-slotted inclusions.

I. Introduction

SURFACE waves and near fields can lead to coupling between coplanar and patch antennas [1]–[3]. The near-field coupling arises when an antenna is placed in the near-field zone of another antenna. The near-field coupling is strong in situations where the antennas are printed on dielectric substrates with very low permittivity [3]. In such scenarios, the coupling can result in severe degradation to the antenna's radiation characteristics. While surface waves are weakly excited in very thin grounded dielectric substrates, space-waves dominate and show strong coupling when antennas are in close proximity.

Several methods to reduce the mutual coupling between patch antennas were reported in the literature. In [4] and [5], electromagnetic band-gap (EBG) structures using the mushroom-like topology were used. However, the structures involved plated through-holes (vias), which are not attractive from the electric loss and manufacturing perspective. In [5], planar EBG structures were used, eliminating the need for vias, however incurring the complexity and cost of using two dielectric layers. In [6], spiral resonators were embedded within the dielectric substrate, requiring an elaborate fabrication process and increased losses in the antenna system.

Complementary split-ring resonator (CSRR) structures were used for harmonic rejection and filtering [7]. The CSRR [see Fig. 1(a)] electromagnetic behavior is best understood by applying the duality principle to the magnetically resonant SRR structures [8]. The SRR-based magnetic materials react to the vertically polarized (with respect to the SRR's plane) magnetic fields. Their resonance behavior is due to the induced electromotive force that generates a current that flows within the metallic rings and gaps, producing a balanced inductive-capacitive effect. From duality, the CSRR exhibits resonant behavior in the presence of vertically polarized electric fields [9]. Therefore, such structures have proven to be particularly useful in an electromagnetic environment where the electric field is dominantly vertically polarized.

In this letter, mutual coupling reduction between two patch antennas is achieved by introducing a novel CSRR cell. Fig. 1 shows the unit cells of the CSRR [Fig. 1(a)] and the new structure [Fig. 1(b)], which will be referred to as the slotted-CSRR (SCSRR). Full-wave simulation is used to investigate the effects of the SCSRR on the antenna's parameters. The new configuration is implemented by etching away the copper sections from the ground plane. The fabrication does not require any modifications to the existing dielectric substrate. Consequently, the antenna remains low-profile and lightweight, and the far-field properties are practically left unchanged.

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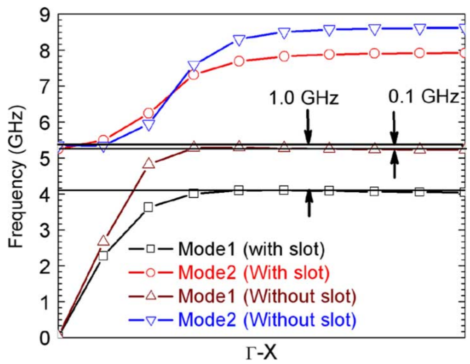


Fig. 2. Dispersion diagrams for SCSRR and CSRR unit cells.

II. SCSRRs Characterization

The proposed structure as shown in Fig. 1(b) consists of two complementary SRRs connected with a slot of length $L_{\rm s}$ and width $W_{\rm s}$. Eigenmode analysis was performed using the full-wave 3-D simulation tool CST Microwave Studio to demonstrate the filtering characteristics of the proposed structure. The corresponding Brillouin diagram for an infinite SCSRR structure is plotted along the Γ–X axis of the periodic structure as shown in Fig. 2. The dimensions of the SCSRR unit cells were optimized to obtain a rejection band from 4.0 to 5.1 GHz. The optimized dimensions are $L = 4$ mm, $a = b = g = 0.2$ mm, $L_{\rm s} = 2$ mm, and $W_{\rm s} = 0.35$ mm (see Fig. 1). The inclusions are etched on a dielectric substrate ($\epsilon_r = 3.48$, $\tan\delta = 0.004$) with a thickness of 1.27 mm. The separation distance between the unit cells is 1 mm.

Strong rejection characteristics are observed for the SCSRRs, where the band-gap zone is clearly seen within the designed frequency range. To demonstrate the effectiveness of the slot in comparison to the traditional CSRR cell, a comparative eigenmode analysis is given in Fig. 2. Clearly evident from Fig. 2, a larger unit cell (4.5×4.5 mm^2) is needed to achieve suppression around 5 GHz, resulting in a narrow rejection band of 0.1 GHz as compared to the 1-GHz rejection band of the SCSRR cell. The wide stopband behavior of the proposed unit cell resonator (CSRR with slot) can be viewed as two cascaded filters. An alternative demonstration of the band-gap behavior of the SCSRR is possible by computing the scattering parameters of a microstrip transmission line placed over the aforementioned dielectric substrate and backed by three SCSRR inclusions, in a manner identical to the experiments discussed in [7]. From the scattering parameters, the attenuation constant can be extracted, and indeed, it was found to be appreciable over the band-gap shown in Fig. 2. While it should be noted that the electric field behavior under a microstrip line is not identical to that of the electric field within the substrate of the two antennas, the similarities exist in that a significant normal (to the ground plane) electric field component is present in the two scenarios.

III. Mutual Coupling

The setup model used to demonstrate the mutual coupling reduction is shown in Fig. 3, where two identical coplanar microstrip antennas having a resonant frequency of 5 GHz are placed $0.25\lambda_0$ apart, where λ_0 is the free-space wavelength. The square patches have an area of 15×15 mm^2 with the overall board size given by $1.3\lambda_0 \times 1.0\lambda_0$. The antennas are placed over a dielectric substrate ($\epsilon_r = 3.48$, $\tan\delta = 0.004$, and thickness $h = 1.27$ mm). As shown in Fig. 3, the SCSRRs are etched out in such a way that the Γ–X axis of the periodic structure (see Fig. 2) coincides with the line joining the center of the two patch antennas. This configuration ensures the suppression of the vertically polarized electric fields (space-wave) between the two patches. The transmission coefficient between the two patches is determined to gauge the mutual coupling effect.

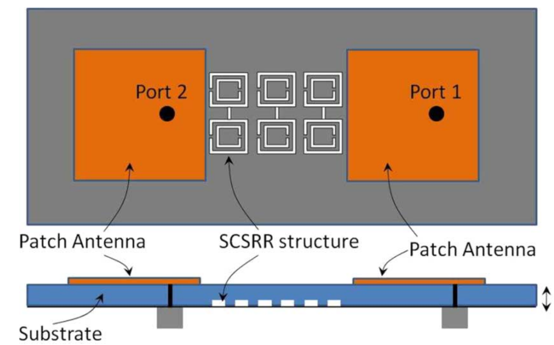


Fig. 3. Top and side views for the two patch antennas with the SCSRR etched on the ground plane. Note that the gray area surrounding the patch antennas represents ground plane metallization.

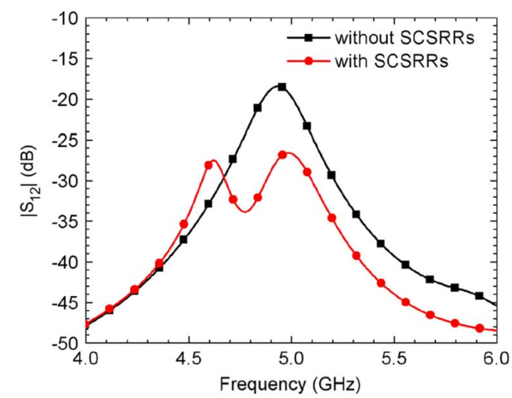
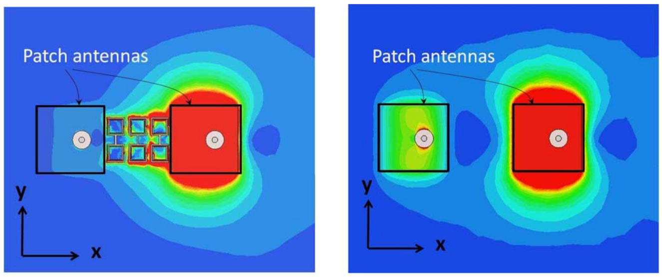


Fig. 4. Mutual coupling comparison for the two patch antennas with and without SCSRRs.

Fig. 4 shows the mutual coupling between the two patch antennas with and without the SCSRR inclusions. A reduction of about 10 dB in the mutual coupling between the antennas is observed. Note that the resonance of the SCSRR in the presence of the antennas corresponds to the dip in the $|S_{12}|$, which occurs at approximately 4.7 GHz. Since the substrate is thin ($h/\lambda_0 = 0.025$), the dominant field is a space-wave with vertical electric field above the ground plane. The mitigation of the space-wave by virtue of the band-gap filtering is clearly observed in Fig. 5(a), in which the distribution of the surface currents on the ground plane is plotted when one antenna is excited while the other antenna is terminated with a 50-Ω impedance. Without the SCSRRs, high concentration of the surface currents is seen in the loaded antenna. The inclusion of SCSRR results in only a slight shift in the resonant frequency of the patches, as depicted in the reflection coefficient plot in Fig. 6.

The antenna gain patterns were computed by exciting one of the antennas and loading the other with a 50-Ω impedance. The



(a) (b)

Fig. 5. Snapshots for the surface current within the finite ground plane for (a) the SCSRRs case and (b) solid ground (no SCSRRs resonators).

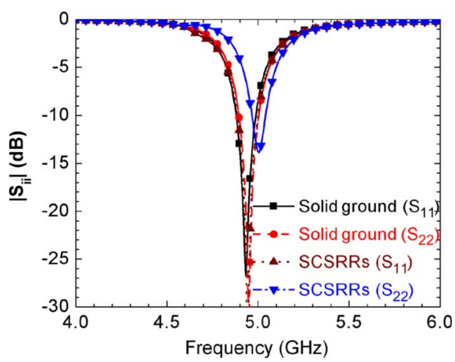


Fig. 6. Reflection coefficient computed for the two patches with and without SCSRRs.

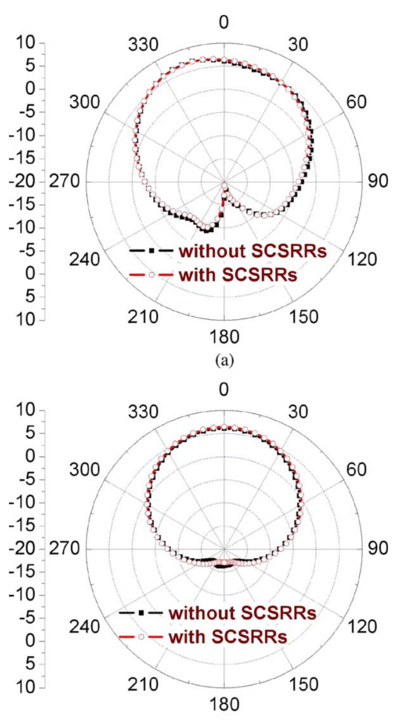


Fig. 7. Far-field gain patterns of the two patches with and without SCSRRs resonators at 5 GHz. (a) E-plane. (b) H-plane.

E- and H-plane patterns, depicted in Fig. 7(a) and (b), respectively, do not show any significant difference between the main lobes patterns. Furthermore, the antenna's efficiency (calculated numerically) does not show any notable change at the operating frequency.

IV. Conclusion

A new subwavelength resonator, referred to as the slotted CSRR (SCSRR), is produced by bridging two traditional CSRR cells through a slot. The CSRR connected by a slot can be viewed as two cascaded filters. The slot in a ground plane has been well known to provide a low-pass response in a certain frequency range [10]. The dimensions of CSRRs and slots are adjusted so that their individual stopbands are connected in frequency, resulting in a wideband response. An equivalent circuit model of the presented structure is under development and will be the subject of a future publication.

The properties of the SCSRR are verified by dispersion analysis. The SCSRRs reduce the mutual coupling between two coplanar microstrip patch antennas spaced by a quarter free-space wavelength. The reduction is possible because of the ability of the SCSRRs to efficiently suppress the electric fields normal to the ground plane, which in turn reduces the surface currents in the terminated antenna element. A 10-dB reduction in the mutual coupling is observed when three SCSRR cells are placed in the ground plane between the patches. A study of far-field properties shows no significant change in individual antenna E- and H-plane patterns. Furthermore, unlike EBG- and SRR-based coupling reduction methods, no additional metallic structures are embedded inside the substrate.

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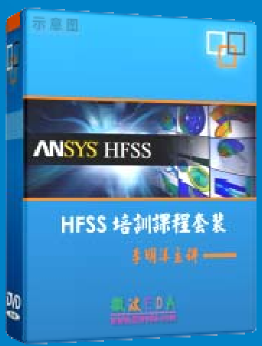

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